Prediction of times of facial and finger freezing during cold air exposure

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Abstract

The Cold Exposure Survival Model (CESM) has undergone various modifications since its inception as a decision aid for Search and Rescue. The present change is the addition of the prediction of the risk of frostbite of the cheek and finger. This risk is not confined to just the casualty, but it might also apply to the rescuers. Hence, predictions on the risk of frostbite and its rate of onset would markedly augment CESM by providing a more complete assessment of the casualty's survival status, and the risk to the rescuers, especially when bare hands are unavoidable. These predictions should also help increase public awareness on the risk of frostbite and potentially alleviate the incidence and severity of cold injury. This report outlines a methodology for calculating the risk and onset times of frostbite of the bare cheeks and fingers. Times to freezing are considerably more informative and less likely to be misinterpreted than the conventional use of the wind chill temperature, which can be misleading.

Résumé

Le Modèle de survie à l'exposition au froid (MSEF) a subi divers changements depuis son adoption comme outil de prise de décisions dans le cadre des opérations de recherche et de sauvetage. Le changement dont il est question dans ce rapport consiste à intégrer à ce modèle la prévision du risque de gelures au niveau des joues et des doigts. Ce risque ne concerne pas seulement la victime mais peut aussi s'appliquer aux sauveteurs. Aussi, les prévisions quant au risque de gelures et à la durée de la période précédant leur apparition amélioreraient nettement le MSEF en permettant de mieux évaluer l'état de la victime ainsi que les risques auxquels les sauveteurs sont exposés, en particulier lorsqu'ils sont contraints de travailler les mains nues. Ces prévisions devraient permettre de sensibiliser le public aux risques de gelures et pourraient entraîner une diminution de la fréquence et de la gravité des lésions causées par le froid. Ce rapport décrit une méthode servant à calculer le risque de gelures aux joues et aux doigts nus ainsi que leur délai d'apparition. Cette dernière donnée en dit beaucoup plus et est moins susceptible d'être mal interprétée que l'indice de refroidissement éolien qui est utilisé habituellement et qui peut être trompeur.

Executive summary

The Cold Exposure Survival Model (CESM) was developed as a decision aid for Search and Rescue (SAR). Its purpose is to predict the likely time of survival for cold-exposed individuals, whether on land or immersed in water. However, well before an individual's life is at risk of lethal hypothermia, that individual might succumb to the debilitating effects of frostbite. The risk of frostbite is not only confined to the casualty, but it might also threaten the rescuers, especially if bare hands are unavoidable. Hence, predictions on the risk of frostbite and its rate of onset would enhance CESM by providing a more complete assessment of the casualty's survival status, and the risk to the rescuers. This report outlines a methodology for calculating this risk to bare cheeks and fingers based on a mathematical model for predicting the rate of tissue cooling.

Since the cheek has been the focus of wind chill forecasting, it was natural to include it in the revised CESM, whereas the finger has been included for practical considerations, as the fingers are deemed more important for self-help and SAR operations. Even if the fingers are well-protected, the relevance of predicting bare finger cooling is that its rate pertains closely to narrow facial features such as the nose. Since the finger cools at approximately six times as fast as the cheek, it would be prudent to note this difference as a conservative estimate for the most susceptible facial features.

An important difference between the present model prediction and the wind chill temperature (WCT) is that the former calculates the risk of frostbite and its time of occurrence, whereas the latter expresses a subjective sensation based on steady state conditions (i.e., after skin temperature reaches a constant value after the initial exposure to cold). It turns out that the same WCT can be found for various combinations of air temperature and wind speed, but the onset of freezing will be different amongst these combinations. This ambiguity is a potential source of confusion that that can lead to harmless misinterpretation in the uneventful case and damaging forecasting in the worst case. Predicting the time of freezing is proposed as a more meaningful and safer forecast. The methodology for calculating the risk and onset times of frostbite of the bare cheeks and fingers is outlined in this report.

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Sommaire

Le Modèle de survie à l'exposition au froid (MSEF) a été créé pour faciliter la prise de décisions dans le cadre des opérations de recherche et de sauvetage. Il permet de prévoir la durée de survie des personnes exposées au froid, y compris lorsqu'elles se trouvent dans l'eau. Toutefois, bien avant de risquer de mourir d'hypothermie, une personne peut subir les effets invalidants des gelures. Le risque de gelures ne concerne pas que la victime mais peut aussi menacer les sauveteurs, en particulier lorsqu'ils sont contraints de travailler les mains nues. Aussi, les prévisions quant au risque de gelures et à leur délai d'apparition amélioreraient nettement le MSEF en permettant de mieux évaluer l'état de la victime ainsi que les risques auxquels les sauveteurs sont exposés. Ce rapport décrit une méthode servant à calculer le risque de gelures aux joues et aux doigts nus ainsi que leur délai d'apparition; cette méthode est fondée sur un modèle mathématique servant à prévoir la vitesse de refroidissement des tissus.

Étant donné que les joues sont un élément central des prévisions relatives au refroidissement éolien, il semblait naturel de les inclure dans le nouveau MSEF. De leur côté, les doigts ont été inclus pour des considérations d'ordre pratique, étant donné qu'on les considère plus importants pour les opérations de recherche et de sauvetage et pour permettre à la victime de s'aider. Même lorsque les doigts sont bien protégés, il est pertinent de pouvoir prévoir la vitesse de refroidissement des doigts nus, car elle correspond sensiblement à celle des petites zones du visage, le nez par exemple. Étant donné que les doigts se refroidissent environ six fois plus vite que les joues, il serait prudent de prendre note de cette différence afin d'établir une estimation prudente quant aux zones du visage les plus à risque.

Une des grandes différences entre le présent modèle de prévision et l'indice de refroidissement éolien (IRE) tient au fait que le modèle permet de calculer le risque de gelures et leur délai d'apparition, tandis que l'indice exprime une sensation subjective fondée sur des conditions stables (soit après que la température de la peau a atteint une valeur constante à la suite de l'exposition initiale au froid). Or, il se trouve que différentes combinaisons de température de l'air et de vitesse du vent peuvent donner le même IRE, même si le délai d'apparition des gelures varie selon ces différentes combinaisons. Cette ambiguïté peut, dans le meilleur des cas, entraîner une erreur d'interprétation sans conséquence, mais peut aussi avoir une issue néfaste. La prévision du délai d'apparition des gelures est proposée comme méthode à la fois plus utile et plus sécuritaire. La méthode permettant de calculer le risque de gelures des joues et des doigts nus et leur délai d'apparition est décrite dans ce rapport.

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Background

Frostbite is an ever-present risk in most of Canada during certain times of the year. Its occurrence can impose severe limitations to a survivor during a search and rescue (SAR) operation. Historically, frostbite has accounted for over 90% of casualties exposed to cold during SAR operations in the far north (Mills 1993). Predictions on the risk of frostbite and its rate of onset would markedly augment the Cold Exposure Survival Model (CESM; Tikuisis 1995, 1997) by providing a more complete assessment of the casualty's survival status. CESM presently predicts the survival time of individuals exposed to cold air and/or immersed in cold water, and thus the addition of freezing risk should facilitate decision-making during SAR operations.

Severe cold wind can also impose a debilitating stress on rescuers. Any improvement in the prediction of the risk of frostbite should be helpful for the prevention of injury, the optimization of equipment use and procedures, and SAR contingency planning. The prediction of frostbite also goes beyond its primary role as a SAR decision aid; it has valuable potential for training instruction and public education.

Public availability of the predictions on the time to freezing should also diminish a general misunderstanding of the effects of wind chill. Bryan Smith of Environment Canada reported, "people get very confused" regarding the interpretation of wind chill (Toronto Star, 15 Mar 2002). Predictions stated in terms of time to freezing are considerably more informative and less likely to be misinterpreted. Forecasting the risk of freezing in these terms and providing public access to a web site might potentially reduce the incidence of freezing cold injury. Increased public awareness of the risk of frostbite might also alleviate the severity of casualty cold injury problems that often confront SAR personnel.

This report outlines the predictions of times to freezing of the bare cheek and finger. Algorithms for these predictions and guidelines for their implementation are detailed, and their inclusion into CESM is described.

Facial cooling

Introduction

Siple and Passel (1945) pioneered the use of the wind chill index to provide guidance on the increased severity of skin cooling due to a combination of cold air and wind. Their findings gained popular use for several decades, but recent investigations have undermined this acceptance. Kessler (1993), Osczevski (1995), and Bluestein and Zecher (1999) have identified weaknesses with the Siple and Passel model, primarily with regard to the absence of physiological and anatomical considerations of tissue cooling. The cheek was specifically targeted, as it is considered the most relevant body region for wind chill estimation. Corrections to the original formulation were subsequently proposed by Osczevski (2000) and ratified by expert consensus (Maarof and Bitzos 2000). These changes resulted in the adoption of the Wind Chill Temperature (WCT) in 2002 by North American meteorological services.

Despite the vast improvement in forecasting the cooling effect of cold air and wind, there are two main outstanding issues regarding the interpretation and basis of the WCT. The WCT is not uniquely linked to the risk of freezing; that is, there is no one-to-one correspondence between the WCT, which is based on steady state conditions after the initial exposure to cold, and the time to freezing. Unfortunately, this is potentially confusing since there are many combinations of air temperature and wind speed that yield the same WCT. It turns out that a higher wind condition is associated with a faster onset of freezing (Tikuisis and Osczevski 2002, 2003). For example, the combinations of -45°C and 5 $km \cdot h^{-1}$ wind (at 10 m off the ground), and -35°C and 35 $km \cdot h^{-1}$ wind both yield a WCT of -53°C. Yet, there is a less than 5% risk of cheek freezing associated with the former condition and a predicted certainty of freezing with an onset time of between 2 and 4 min in the latter condition. An additional potential source of confusion is the counter intuitive result that WCT is negative for air temperatures up to 6°C depending on wind speed, suggesting a possible risk of freezing when none exists.

The other outstanding issue concerns the linkage between the WCT and vulnerability to skin cooling. A high value of the cheek thermal resistance implies low heat transfer through the cheek thereby resulting in a low cheek surface/skin temperature, and consequent greater risk of freezing. However, a low rate of heat flow corresponds to a low wind chill factor (based on the original formulation of the wind chill index) and consequent less severe WCT. Conversely, a low value of the cheek thermal resistance would result in a higher rate of heat flow and a higher skin temperature with the paradoxical result that such a condition corresponds to a higher wind chill factor and more severe WCT, yet the risk of freezing is less.

While the concept of the WCT is intuitively appealing, its inherent ambiguities are a potential source of confusion that can lead to harmless misinterpretation in the uneventful case and damaging forecasting in the worst case. WCT is based on steady state considerations that do not provide times to freezing (times shown on WCT charts are by association with steady state rates of heat loss). Herein, an alternative method of predicting the risk of freezing is proposed based on a dynamic mathematical model that predicts the time to freezing. Risk in the present context implies a finite chance of occurrence.

Revised wind chill chart

The conventional rationale of using a high value of the cheek thermal resistance (R) to yield a conservative prediction of cheek cooling rates is adopted herein. R defines the resistance of the cheek tissue to the flow of heat; low values are associated with high rates of heat loss and vice-versa. Recent measurements on six males and six females indicate that the 95th percentile value of R is approximately 0.075 $m^2 \cdot K \cdot W^{-1}$ [Osczevski (unpublished)]. This value corresponds closely to the cheek-to-core thermal resistance of 0.09 $m^2 \cdot K \cdot W^{-1}$ used to establish the WCT, considering that ~ 80% of the overall resistance is attributed to the cheek alone.

Tables 1 and 2 display the predicted cheek freezing times (based on a skin temperature of -4.8°C; Danielsson 1996) using the above 95th percentile estimate of R, which is associated with a high susceptibility to freezing. The wind speed, v_{10}, pertains to its value at 10 m off the ground, which is the meteorological reference point for wind chill estimates (v_{10} is approximately 50% higher than at face level). All times to freezing were predicted using the dynamic model described in Tikuisis and Osczevski (2002, 2003), which has been validated against several sets of data involving cheek cooling. The risk of freezing for an air temperature (Ta) = - 5°C (not shown) is possible, but unlikely.

Table 1. *Predicted times (min) to cheek freezing for susceptible individuals where Ta is the air temperature and v_{10} is the wind speed at 10 m off the ground. The numbers in parentheses that describe the colour scales refer to the Freezing Index (Table 4).*

Wind v_{10} (km/h)	Ta (°C) -10	-15	-20	-25	-30	-35	-40	-45	-50
5	very low	very low	very low	likely	likely	25.2	17.0	13.2	10.7
10	very low	very low	likely	likely	17.0	11.9	9.2	7.4	6.1
15	very low	likely	likely	17.9	11.5	8.4	6.5	5.2	4.3
20	very low	likely	24.1	13.1	8.9	6.6	5.1	4.1	3.4
25	very low	likely	19.4	10.7	7.3	5.4	4.2	3.4	2.8
30	very low	likely	15.4	9.0	6.3	4.6	3.6	2.9	2.3
35	likely	likely	13.0	7.9	5.5	4.0	3.1	2.5	2.0
40	likely	likely	11.4	7.0	4.9	3.6	2.8	2.2	1.8
45	likely	likely	10.2	6.3	4.4	3.2	2.5	2.0	1.6
50	likely	23.7	9.3	5.8	4.0	2.9	2.3	1.8	1.5
55	likely	19.6	8.5	5.3	3.7	2.7	2.1	1.7	1.3
60	likely	17.1	7.9	4.9	3.4	2.5	1.9	1.5	1.2
65	likely	15.4	7.3	4.6	3.2	2.3	1.8	1.4	1.2
70	likely	14.1	6.9	4.3	3.0	2.2	1.7	1.3	1.1
75	likely	13.0	6.5	4.0	2.8	2.0	1.6	1.2	1.0
80	likely	12.2	6.1	3.8	2.6	1.9	1.5	1.2	1.0

very low	freezing is possible, but unlikely (1)
likely	freezing is likely > 30 min (2)
high	freezing risk < 30 min (3)
severe	freezing risk < 10 min (4)
extreme	freezing risk < 3 min (5)

Table 2. *Predicted cheek freezing times (see shaded scale below) for susceptible individuals with superimposed WCT (°C), where Ta is the air temperature and v_{10} is the wind speed at 10 m off the ground. The numbers in parentheses that describe the colour scales refer to the Freezing Index (Table 4).*

Wind v_{10} (km/h)	Ta (°C) -10	-15	-20	-25	-30	-35	-40	-45	-50
5	-13	-19	-24	-30	-36	-41	-47	-53	-58
10	-15	-21	-27	-33	-39	-45	-51	-57	-63
15	-17	-23	-29	-35	-41	-48	-54	-60	-66
20	-18	-24	-30	-37	-43	-49	-56	-62	-68
25	-19	-25	-32	-38	-44	-51	-57	-64	-70
30	-20	-26	-33	-39	-46	-52	-59	-65	-72
35	-20	-27	-33	-40	-47	-53	-60	-66	-73
40	-21	-27	-34	-41	-48	-54	-61	-68	-74
45	-21	-28	-35	-42	-48	-55	-62	-69	-75
50	-22	-29	-35	-42	-49	-56	-63	-69	-76
55	-22	-29	-36	-43	-50	-57	-63	-70	-77
60	-23	-30	-36	-43	-50	-57	-64	-71	-78
65	-23	-30	-37	-44	-51	-58	-65	-72	-79
70	-23	-30	-37	-44	-51	-58	-65	-72	-80
75	-24	-31	-38	-45	-52	-59	-66	-73	-80
80	-24	-31	-38	-45	-52	-60	-67	-74	-81

very low	freezing is possible, but unlikely (1)
likely	freezing is likely > 30 min (2)
high	freezing risk < 30 min (3)
severe	freezing risk < 10 min (4)
extreme	freezing risk < 3 min (5)

The multiple occurrences of the same WCT in different zones of freezing risk is due to the asymmetrical rate of cooling discussed earlier. This illustrates the ambiguity and deficiency of the WCT with respect to forecasting the risk of freezing.

The dynamic model prediction of cheek freezing onset times (t_f) is computationally quite demanding. As an alternative, an excellent approximation of t_f was found by regressing its value against air temperature and wind speed. The resultant algorithm for predicting the risk and onset time of cheek freezing is outlined in Table 3.

Table 3. *Algorithm for predicting the risk and onset time (t_f in min) of cheek freezing. Ta is the air temperature, v_{10} is the wind speed (km·h^{-1}) at 10 m off the ground, Tss is the steady state cheek skin temperature (see derivation in the Appendix), and FI is the Freezing Index defined in Table 4.*

Ta (°C)	Risk and Time of Freezing
≥ 0	FI = 0 (i.e., no risk of cheek freezing)
0 > T_a > -5	FI = 0 if T_{ss} > 0°C; else FI = 1
-5 ≥ T_a ≥ -12	FI = 0 if T_{ss} > 0°C; FI = 1 if 0 > T_{ss} > -4.8°C; else FI = 2
-13	FI = 1 if v_{10} < 70 km·h^{-1}; else FI = 2
-14	FI = 1 if v_{10} < 55 km·h^{-1}; else FI = 2
-15 ≥ T_a ≥ -20	FI = 1 if T_{ss} > - 4.8°C; else calculate $t_f = (a + b \cdot v_{10})^{-1/x}$ using parameter Set #1; if t_f > 20 min, then report t_f as between 20 and 30 min (FI = 3)
< -20	FI = 1 if T_{ss} > - 4.8°C; else calculate $t_f = (a + b \cdot v_{10})^{-1/x}$ using parameter Set #2; if t_f > 20 min, then report t_f as < 30 min (FI = 3)
Model Parameters	
Set #1	$a = 0.1863 + 0.023336 \cdot T_a + 0.000679 \cdot T_a^2$ $b = 0.0043673 + 0.0006543 \cdot T_a + 0.000025641 \cdot T_a^2$ $x = 3.2 + 0.1 \cdot T_a$
Set #2	$a = -0.025403 - 0.00095008 \cdot T_a$ $b = -0.001505 - 0.000055127 \cdot T_a + 0.0000046778 \cdot T_a^2$ $x = 1.05 + 3 \cdot \exp[-0.15 \cdot (-T_a)]$

Discussion

The prediction of freezing onset time is contingent on a number of factors other than the thermal resistance of the cheek. Consequently, the calculated times to cheek freezing should be viewed as approximate and may be better presented categorically. A risk of freezing index (FI) is therefore proposed (see Table 4 below) with reference to Tables 1 and 2.

Table 4. *Freezing Index (FI) based on predicted risk and times to cheek freezing.*

FI	Descriptor	Risk of Freezing
0	no risk	no risk of freezing
1	very low	freezing is possible, but unlikely
2	likely	freezing is likely after 30 min of exposure
3	high	freezing risk within 30 min of exposure
4	severe	freezing risk within 10 min of exposure
5	extreme	freezing risk within 3 min of exposure

It is emphasized, however, that the intent of such warnings is not to suggest that cold weather is something to be feared or avoided, but rather that appropriate clothing be worn when a significant risk of freezing is forecast. The association between FI and the appropriate clothing protection is beyond the scope of this report, but let it suffice that even a single layer of insulative/wind proof material can provide adequate temporary protection under most conditions.

Finger Cooling

Introduction

While the cheek has been the focus of wind chill charts, other body parts such as the finger warrant attention, as the smaller diameter of the finger makes it more susceptible to cold injury than the cheek (Wilson 1967). The finger might also be generally perceived as better and more often protected than the face; however, it would be prudent to tabulate safe exposure limits for the bare finger, especially for those individuals who rely on bare hand function during cold exposure, whether by design or accident (Dusek 1957). Contact with cold materials poses additional risk that is not covered herein; readers are referred to Havenith et al. (1991) and Chen et al. (1994) for further information on this aspect of potential cold injury. Further, the narrow geometry of the fingers resembles certain features of the face, such as the nose, and as the fingers are expected to cool faster than the cheek, safe exposure limits for the finger can potentially be a warning for cooling of the more susceptible regions of the face. That is, the prediction of finger freezing can be viewed as a conservative warning of wind chill for general application.

Regression of finger freezing times

The dynamic cooling model used for predicting cheek cooling can be applied for finger cooling through a reconfiguration of the model geometry and parameterization. Predictions of finger cooling were found to agree with several reported observations by accounting for the reduction of blood flow to the finger due to its vasoconstrictive response to cold (Tikuisis 2004).

The calculations involved are computationally demanding, and an alternative method via regression was sought, analogous to the method for predicting the rate of cheek cooling. In this case, however, the algorithm is less complicated and can be expressed by the following single formulation:

$$t_f = \left(-1.66\text{x}10^{-2} - 7.3011\text{x}10^{-4} \cdot T_a \cdot v_{10}{}^{0.4783}\right)^{-1.786}$$

where t_f is the onset time (in s) of finger freezing, T_a is the air temperature (°C), and v_{10} is the wind speed (km·h^{-1}) at 10 m off the ground. The onset of finger freezing is based on skin cooling times to - 4.8°C (onset of freezing; Danielsson 1996) for a bare finger of an assumed radius of 1 cm in a crosswind at a zero angle of attack. Predictions of t_f that exceed 240 s using the above formulation are not reliable and are re-estimated as follows. If T_{ss} of the finger (see Appendix) > 0°C, then there is no risk of freezing. If 0 • T_{ss} • -4.8°C, then freezing is possible, but unlikely. If T_{ss} < -4.8°C, then t_f is based on the prediction for the cheek such that if t_f (cheek) < 30 min, then t_f (finger) < 5 min, and if t_f (cheek) > 30 min, then t_f (finger) > 5 min. These predictions are summarized categorically in Table 5.

Table 5. *Categories of predicted freezing risk of the finger.*

Risk of Freezing
no risk of freezing
freezing is possible, but unlikely
freezing is likely after 5 min of exposure
freezing risk within 5 min of exposure
freezing risk within 2 min of exposure
freezing risk within 1 min of exposure

Discussion

The asymmetrical cooling rates of the cheek discussed earlier also occurs for the finger whereby the predicted onset of freezing is faster in higher winds for combinations of T_a and v_{10} that result in the same WCT. For example, the combinations of - 45°C and 5 km·h^{-1} wind (at 10 m off the ground), and -35°C and 35 km·h^{-1} wind both yield a WCT of -53°C, yet the predicted time to finger freezing is between 2 and 4 min, and between 30 and 60 s in the former and latter cases, respectively. Times to freezing, or safe exposure limits (such as FI in Table 4), would be less confusing and more meaningful to report than the WCT. Determining which body location, finger or cheek, should be used in risk assessments is a choice that might depend on a population's specific requirement.

That the WCT has been based on cheek cooling reflects the cheek's sensitivity to cold and the likelihood that the face is often bare (Osczevski 1995). However, the nose is as likely to be exposed as the cheek and is far more susceptible to freezing due to its narrow geometry, as noted for the finger. Indeed, the nose tends to freeze in approximately one-third the time that it takes the cheek to freeze (Siple and Passel 1945). The model predictions above suggest that the finger freezes in about 1/6th the time taken for the cheek. Forecasting the risk of finger freezing would represent the most conservative estimate as it pertains more closely to the susceptible segments of the face than if only the risk of cheek freezing was given.

Revised CESM

Predictions of times to freezing for both cheek and finger cooling have been transcribed into a simple function using MS-Visual Basic 6.0. This function will be incorporated as an upgrade to the Cold Exposure Survival Model (CESM) using the same environmental inputs for the calculation of survival times. Figure 1 provides an example of the proposed interface modification with the function inputs and outputs indicated by open parentheses.

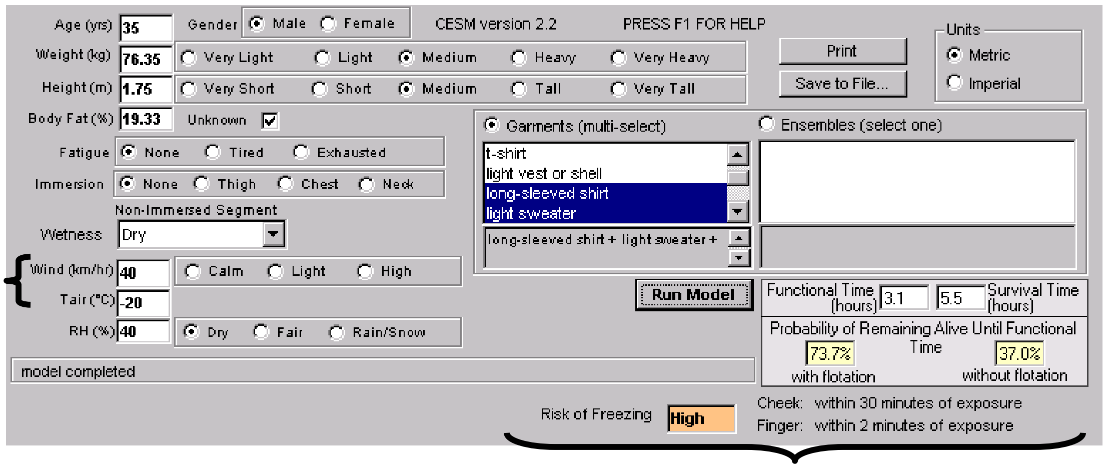

***Figure 1.** Proposed CESM interface, indicating relevant environmental inputs and time to freezing estimates.*

As time to freezing estimates of the cheek and finger require both ambient temperature and wind speed as inputs, freezing times will only be available for incidents where air exposure is indicated and the air temperature is below 0°C. In order to provide a simple and easily interpreted output that is also consistent with convention, the freezing index descriptor for the cheek is used. This output is derived from Table 4 and is colour coded according to increasing risk severity (green to red). In addition, risks and times of freezing are displayed according to Tables 4 and 5 for the cheek and finger, respectively.

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List of symbols/abbreviations/acronyms/initialisms

CESM	Cold Exposure Survival Model
DND	Department of National Defence
FI	Freezing Index
SAR	Search and Rescue
WCT	Wind Chill Temperature

Glossary

R	thermal resistance ($m^2 \cdot °C \cdot W^{-1}$)
T_a	air temperature (°C)
T_{ss}	steady state temperature (°C)
t_f	time to freezing (s or min)
v_{10}	wind speed ($km \cdot h^{-1}$) at 10 m off the ground

Appendix: Determination of the steady state skin temperature (T_{ss}); see Table A below for parameter values.

steady state skin temperature (°C): $$T_{ss} = \frac{R \cdot (h_c \cdot T_a + h_r \cdot T_r) + T_c}{R \cdot (h_c + h_r) + 1}$$

convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$): $$h_c = \frac{Nu \cdot k_{air}}{2r_s}$$

radiative heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$): $$h_r = 4 \cdot \varepsilon \cdot \sigma \cdot [273.15 + (T_s + T_r)/2]^3$$

Nusselt number: cheek: $Nu = 1.14 \cdot Re^{0.5} \cdot Pr^{0.4} \cdot [1 - (50/90)^3]$

finger: $Nu = 0.193 \cdot Re^{0.62} \cdot Pr^{0.33}$

Reynolds number: $$Re = \frac{2r_s \cdot v \cdot \rho_{air}}{\mu}$$

Prandt number: $$Pr = \frac{\mu \cdot c_{air}}{k_{air}}$$

thermal conductivity of air ($W \cdot m^{-1} \cdot K^{-1}$): $$k_{air} = 0.024009 + 0.000038134 \cdot (T_a + T_{so})$$

density of air ($kg \cdot m^{-3}$): $$\rho_{air} = 1.3033 - 0.0025945 \cdot (T_a + T_{so})$$

dynamic viscosity of air ($kg \cdot m \cdot s^{-1}$): $$\mu = (170.82 + 0.26718 \cdot (T_a + T_{so})) \cdot 10^{-7}$$

mean radiant temperature (°C): $$T_r = 0.5 \cdot (T_a + T_\infty)$$

atmospheric radiant temperature (°C): $$T_\infty = (273.15 + T_a) \cdot \left(0.6 + 0.05 \cdot \sqrt{P_a}\right)^{0.25} - 273.15$$

ambient vapour pressure (mbar): $$P_a = 9.87 \cdot (\%RH/100) \cdot e^{[16.6536 - 4030.183/(235 + T_a)]}$$

and where R is the thermal resistance ($m^2 \cdot °C \cdot W^{-1}$) and T_a is air temperature (°C)

Table A. *Parameter values for equations listed above [see Tikuisis and Osczevski (2002, 2003) and Tikuisis (2004) for further details].*

Parameter	Cheek	Finger
outer shell radius, r_s	0.069 m	0.010 m
skin temperature, T_s	iterate*	iterate*
initial skin temperature, T_{so}	32°C	0°C
inner surface/core temperature, T_c	34°C	-1°C if $T_a < -5$°C else $T_a + 4$°C
wind speed on the skin in $m \cdot s^{-1}$, v	$(2/3/3.6) \cdot v_{10}$	$(2/3/3.6) \cdot v_{10}$
thermal resistance, R	0.075 $m^2 \cdot °C \cdot W^{-1}$	0.00776 $m^2 \cdot °C \cdot W^{-1}$**
specific heat of air, c_{air}	1010 $W \cdot s \cdot kg^{-1} \cdot °C^{-1}$	1010 $W \cdot s \cdot kg^{-1} \cdot °C^{-1}$
emissivity of skin, ε	0.94	0.94
Stefan-Boltzmann constant, σ	5.67x 10^{-8} $W \cdot m^{-2} \cdot °C^{-4}$	5.67x 10^{-8} $W \cdot m^{-2} \cdot °C^{-4}$

* assume T_{so} as the starting value of T_s for the first estimation of T_{ss}, and then apply this estimate as the starting value of T_s for the final estimation of T_{ss}

** yields a thermal conductivity of 0.24 $W \cdot m^{-1} \cdot K^{-1}$, which is characteristic of cold tissue, when coupled with an assumed inner core radius of 0.0083 m

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14. ABSTRACT

(U) The Cold Exposure Survival Model (CESM) has undergone various modifications since its inception as a decision aid for Search and Rescue. The present change is the addition of the prediction of the risk of frostbite of the cheek and finger. This risk is not confined to just the casualty, but it might also apply to the rescuers. Hence, predictions on the risk of frostbite and its rate of onset would markedly augment CESM by providing a more complete assessment of the casualty's survival status, and the risk to the rescuers, especially when bare hands are unavoidable. These predictions should also help increase public awareness on the risk of frostbite and potentially alleviate the incidence and severity of cold injury. This report outlines a methodology for calculating the risk and onset times of frostbite of the bare cheeks and fingers. Times to freezing are considerably more informative and less likely to be misinterpreted than the conventional use of the wind chill temperature, which can be misleading.

(U) Le Modèle de survie à l'exposition au froid (MSEF) a subi divers changements depuis son adoption comme outil de prise de décisions dans le cadre des opérations de recherche et de sauvetage. Le changement dont il est question dans ce rapport consiste à intégrer à ce modèle la prévision du risque de gelures au niveau des joues et des doigts. Ce risque ne concerne pas seulement la victime mais peut aussi s'appliquer aux sauveteurs. Aussi, les prévisions quant au risque de gelures et à la durée de la période précédant leur apparition amélioreraient nettement le MSEF en permettant de mieux évaluer l'état de la victime ainsi que les risques auxquels les sauveteurs sont exposés, en particulier lorsqu'ils sont contraints de travailler les mains nues. Ces prévisions devraient permettre de sensibiliser le public aux risques de gelures et pourraient entraîner une diminution de la fréquence et de la gravité des lésions causées par le froid. Ce rapport décrit une méthode servant à calculer le risque de gelures aux joues et aux doigts nus ainsi que leur délai d'apparition. Cette dernière donnée en dit beaucoup plus et est moins susceptible d'être mal interprétée que l'indice de refroidissement éolien qui est utilisé habituellement et qui peut être trompeur.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Heat loss; Heat transfer; Wind chill; Face(anatomy); Exposure; Wind velocity; Convection; Body temperature; Temperature; Skin (anatomy); Models; Cold injuries; Frostbite; Cold stress